Structural Geology of the Henbury Meteorite Craters Northern Territory, Australia

By DANIEL J. MILTON

CONTRIBUTIONS TO ASTROGEOLOGY

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A group of small craters that exhibit an unusually wide variety of structural features

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By Daniel J. Milton

ABSTRACT

About 12 meteorite craters lie within a quarter square mile near Henbury, Northern Territory, Australia. Nine craters, some of which are completely filled basins, range in diameter from about 20 to 210 feet. The largest craters form a close group comprising two complete craters about 230 and 300 feet in diameter and two craters about 390 and 480 feet in diameter that overlap to form an oval crater 600 feet long. The depth of the largest crater reaches 50 feet, and the rim is raised about 20 feet above the surrounding surface. The bedrock, belonging to the Winnall Beds of late Precambrian age, consists of weakly indurated shale and siltstone and less abundant moderately indurated sandstone. The bedrock dipped homoclinally about 35° before the impact. The larger craters formed on a gently sloping surface covered by a thin layer of pediment gravel.

Rock exposed in crater walls and rims has been displaced outward from the craters. A variety of mechanisms were involved in the displacement. Three types of folds were recognized in the larger craters:

1. Tangential folds having steeply dipping axial planes. These folds are commonly asymmetric, the limb away from the crater being vertical or overturned, and were formed by compressional stresses radial to the crater. Such folds are dominant in the lower walls.
2. Folds whose axial planes dip toward the crater at low angles, approximately parallel to the crater wall. These folds were formed by shearing stresses parallel to those which produced the wall of the original crater itself. Such folds are shallow and are found where the original crater wall is least eroded.
3. Punchlike folds, convex outward from the crater, having nearly horizontal axial planes. These folds were formed by outward stresses sharply localized within the crater wall.

The craterward limbs of folds of the first type are commonly thrust over the crest; thrust faults parallel the axial planes of folds of the second type and form the boundaries of folds of the third type. Other overthrusts that have low and intermediate dips in the crater walls and on the rims are not closely associated with folds. Underthrusts occur low in the crater walls.

On the downdip side of the Main Crater, the beds steepen upward in the crater wall, becoming vertical and then overturned to form a flap of inverted strata lying on the precrater surface. The units in this flap have been greatly thinned, which indicates that shearing along planes at a small angle to the bedding took place simultaneously with folding. Along part of the rim, the entire axial region of such a synclinal rim fold has been thrust out over the precrater surface. The flanks of the rim farther from the crater are covered by fragmental debris in which fragments from different bedrock units are in general unmixed. Scattered impact-melted glass fragments may represent a layer of fallout from the largest crater that has been nearly removed by erosion.

Rock in the wall between two craters that are close together but do not intersect was thrown into a series of folds with approximately vertical axial planes parallel to the common wall. Where the centers of impact are closer, as in the two craters that form the Main Crater, the middle part of the intervening wall was eliminated, and rock in the outer parts was folded about axes approximately normal to the common chord and thrust outward along the extension of the common chord. Some of the slices were thrust over the precrater surface for as much as 80 feet. The outer edges of some slices are turned under where the main mass has ridden over them. Cross sections through the pile of imbricate slices suggest an Alpine nappe structure. Details of fault surfaces indicate that the structural blocks separated by faults were not in contact during deformation; rather, each block was displaced outward and rotated to a large degree independently of its neighbors. This indicates a momentary dilation that probably resulted largely from the interaction of stresses from the two craters, although there is evidence that some dilation occurred in the walls where only a single crater was involved.

INTRODUCTION

PURPOSE AND SCOPE OF REPORT

Geologic study of the meteorite craters at Henbury, Northern Territory, Australia, was undertaken in 1963 by the U.S. Geological Survey as part of a program of investigations of impact features conducted on behalf of the National Aeronautics and Space Administration. This report briefly describes the crater field as a whole but is primarily concerned with the structural geology of the wall and rimcrest areas of the three largest craters. An earlier report (Milton and Michel, 1965) deals with crater 3, a smaller crater notable for the ray pattern shown by its ejecta. A companion study by E. C. T. Chao of the impact metamorphism associated with the craters is in progress. Certain phases that should be part of a complete study of the craters could not be carried out during the single field season; among these are more detailed mapping of the outer parts of the ejecta blankets and a study of the distribution of meteoritic fragments.

PREVIOUS WORK

Most of the previously available information on the craters derives from the original reconnaissance by Alderman (1932), who was not able to make more than a cursory study of the geologic structure of the craters. Soon after Alderman's expedition, R. Bedford and others collected meteoritic material and excavated some of the smaller craters (Spencer, 1933a). Rayner (1939) made a magnetic survey of the craters. The meteoritic material has been described by Alderman (1932) and Spencer (1933a). A study of the cosmogenic carbon-14 content of the meteoritic iron by Kohman and Goel (1963) indicated a maximum terrestrial age of less than 4,700 years. Impact-melted material from the largest crater has been described by Spencer (1933a), Taylor and Kolbe (1964, 1965), and Taylor (1967). An atlas of excellent photographs and a brief summary of the history of investigation of the craters has been published by Hodge (1965), who also has in progress a study of the distribution of microscopic meteoritic material around the craters. Recent speculations on the mechanics of impact (Baldwin, 1963; Krinov, 1963) are based on the papers of Alderman and Spencer.

FIELDWORK

Fieldwork was begun by F. C. Michel and the author on July 12, 1963. During July planetable geologic maps of craters 3 and 10 and a planetable topographic map of the area of the three largest craters at a scale of 1:360 were made. From August 1 to September 28, the writer, working alone, plotted the geology on the topographic base. A marker was placed at the point where each attitude shown on plate 1 was measured, and each point was located by tape and compass with respect to reference points that had been surveyed by planetable. The topographic base was concurrently revised; as a result, contours in the areas of detailed geology are somewhat more accurate than in other parts of the map.

ACKNOWLEDGMENTS

L. C. Ranford and P. J. Cook, geologists of the Henbury areal mapping party of the Bureau of Mineral Resources of Australia, helped in many ways, including relating the geology at the craters to the regional geology. I am deeply grateful to Reg Smith, manager of Henbury Station, and Mrs. Smith for their unfailing friendliness and help.

The interest and help of many other Australian geologists and residents of the area are also appreciated. W. A. Cassidy, of Lamont Geological Observatory, kindly loaned aerial photographs of the craters and his notes from an earlier visit.

GEOGRAPHIC SETTING

LOCATION AND ACCESS

The Henbury craters lie within a quarter square mile area near long. 133°09′ E. and lat. 24°35′ S. in the Northern Territory, Australia. They are about 7 miles west southwest of Henbury Homestead, 80 miles southwest of Alice Springs, and can be reached by a track from the unpaved highway linking Alice Springs with South Australia. Although they lie within the confines of the Henbury Cattle Station, the craters are protected by the Government as a Territorial Reserve.

CLIMATE, FLORA, AND FAUNA

The geography of central Australia has been described by R. A. Perry and associates (1962); the Chandlers land system of their classification describes the vicinity of the craters well. Annual rainfall is about 8 inches, mostly in summer storms. Mulga (*Acacia aneura*) grows along wet-weather watercourses, but the plains around the craters and the crater walls have only a sparse growth of needlebush (*Hakea leucoptera*) and other shrubs. The floor of the Main Crater is sparsely covered by saltbush (*Atriplex* spp.). The wall of the Water Crater (crater 6) has been breached, and the crater has captured a preimpact drainage system, so that water stands in the crater floor after rains. Consequently, the largest trees in the vicinity grow in this crater, among which whitewood (*Atalaya hemiglauca*) is the dominant species.

Kangaroos and dingoes, the only large members of the native fauna, are occasionally seen at the craters. Cattle browse over the area and enter the craters especially to water after rains, wearing trails down the walls. The band of pediment gravel that crops out beneath ejected bedrock in the upper crater walls is particularly favored by rabbits for burrowing. The activities of human visitors and the fauna they have introduced probably makes the present rate of destruction of the craters many times what it was in the pre-European era.

GEOLOGIC SETTING

The Henbury craters lie at the foot of the Bacon Range, a ridge that rises steeply from just south of the crater field to a crest several hundred feet higher and about 600 feet distant from the nearest craters. Bedrock at the craters, and up to the crest of the Bacon Range, is part of the Winnall Beds of late Proterozoic age (Ranford and others, 1967). The predominantly sandstone Winnall Beds are the lateral equivalent of the predominantly shaly Pertatataka Formation to the north. The boundary has arbitrarily been placed several miles north of the craters. Although the beds at the south edge of the crater field are of Winnall type, the beds at the larger craters actually show typical Pertatataka lithology (P. J. Cook, oral commun., 1965). Lithologic characterization of units in this report is primarily for the purpose of identification, and field terms are retained. Petrographic descriptions and chemical analyses by Taylor and Kolbe (1965) indicate that the shale and siltstone of this report might more precisely be called subgraywacke. A fault near the crest of the Bacon Range brings the older Inindia Beds to the surface. The range is capped by the so-called grey billy, a dense chert formed by near-surface silicification during the Tertiary Period.

The Winnall Beds dip homoclinally to the south, and their differential resistance to erosion determines the topography. The stratigraphically highest exposed beds are hard sandstone which, with the grey billy capping, form the Bacon Range. A second zone of thick-bedded hard sandstone forms a low bare ridge on which craters 10, 11, and 12 lie. Near craters 1–8 the Winnall Beds are composed predominantly of weaker shale and siltstone containing a few thin sandstone beds. As a consequence, bedrock has been corraded to an alluvium-covered pediment that slopes gently northward from the Bacon Range. The rill system south of crater 6 (fig. 1) is older than the craters and suggests that a very low ridge was formed by the sandstone beds intersected by craters 6 and 8.

Exposed beds near the crater field (mostly on the sandstone ridge) consistently strike east-west and dip south about 35 degrees. Despite the major fault in the Bacon Range, no faults and only a few small folds were noted in the Winnall Beds cropping out near the craters. Preimpact deformation may have been greater, however, in the less competent shales and siltstones and may have caused some of the unexplained stratigraphic and structural anomalies. Nevertheless, the structures mapped on plate 1 are assumed to have resulted, with, at most, minor local exceptions, from deformation of a simple homoclinal sequence by meteorite impact.

A small hogback of sandstone shown at the east edge of plate 1 is the only nearby outcrop of the beds intersected by the large craters except those in the crater walls themselves. The stratigraphic sequence is therefore based entirely on exposure of rocks that have been severely disturbed by the impact, and so the sequence is not as well defined as could be desired. About 450 feet of section is exposed in the larger craters, in which eight major units, designated units a through h, and as many subunits have been mapped (pl. 1). The sequence of units e through h resembles that of units a through d, but there are sufficient differences to rule out structural repetition of the section. Instead, a cyclic pattern of deposition in the Winnall Beds seems to be indicated.

The shales and siltstones, which make up the bulk of the section in the area on plate 1, crumble into chips or fragments that are at most a few inches in size, and they can easily be excavated with a shovel. The beds of sandier siltstone and sandstone are more indurated and break into larger plates. Only in the south wall of the Water Crater are sandstone beds sufficiently indurated to break into blocks several feet across.

Bedrock on the pediment is covered by a Quaternary alluvial deposit consisting of cobbles and smaller subrounded fragments of sandstone and grey billy from the Bacon Range and a few rounded pebbles of more distant provenance in a red silty matrix. Coarse fragments are concentrated close to the surface, producing a stony gibber plain. The thickness of this pediment gravel depends on the underlying material—it is thin or even absent over the more resistant sandstone beds and may reach a thickness of 15 feet over shale. In places shale units are weathered as much as 15 feet below the pediment gravel and grade upward into a reddish clayey soil.

SUMMARY DESCRIPTION OF THE CRATERS

Twelve of the 13 craters described and numbered by Alderman (1932) are clearly recognizable; only possible small ill-defined craters can be added to this list (fig. 1). Hodge's atlas (1965) can be consulted for photographs of each crater.

Craters 1 and 2.—No raised rims or closed depressions remain at craters 1 and 2. As recognized by Alderman (1932), however, clay pans free from pediment gravel and supporting a growth of mulgas indicate craters about 80 and 90 feet in diameter that have been nearly obliterated by erosion of their rims and by filling by alluvium.

Crater 3.—Crater 3 has a diameter of 170–230 feet, a depth of 9–15 feet, and a maximum rim height of 4 feet (terminology defined in fig. 2). A detailed map and description of this crater, which is notable for the pattern of ray loops in which ejected fragments from sandstone beds are distributed, has been published previously (Milton and Michel, 1965).

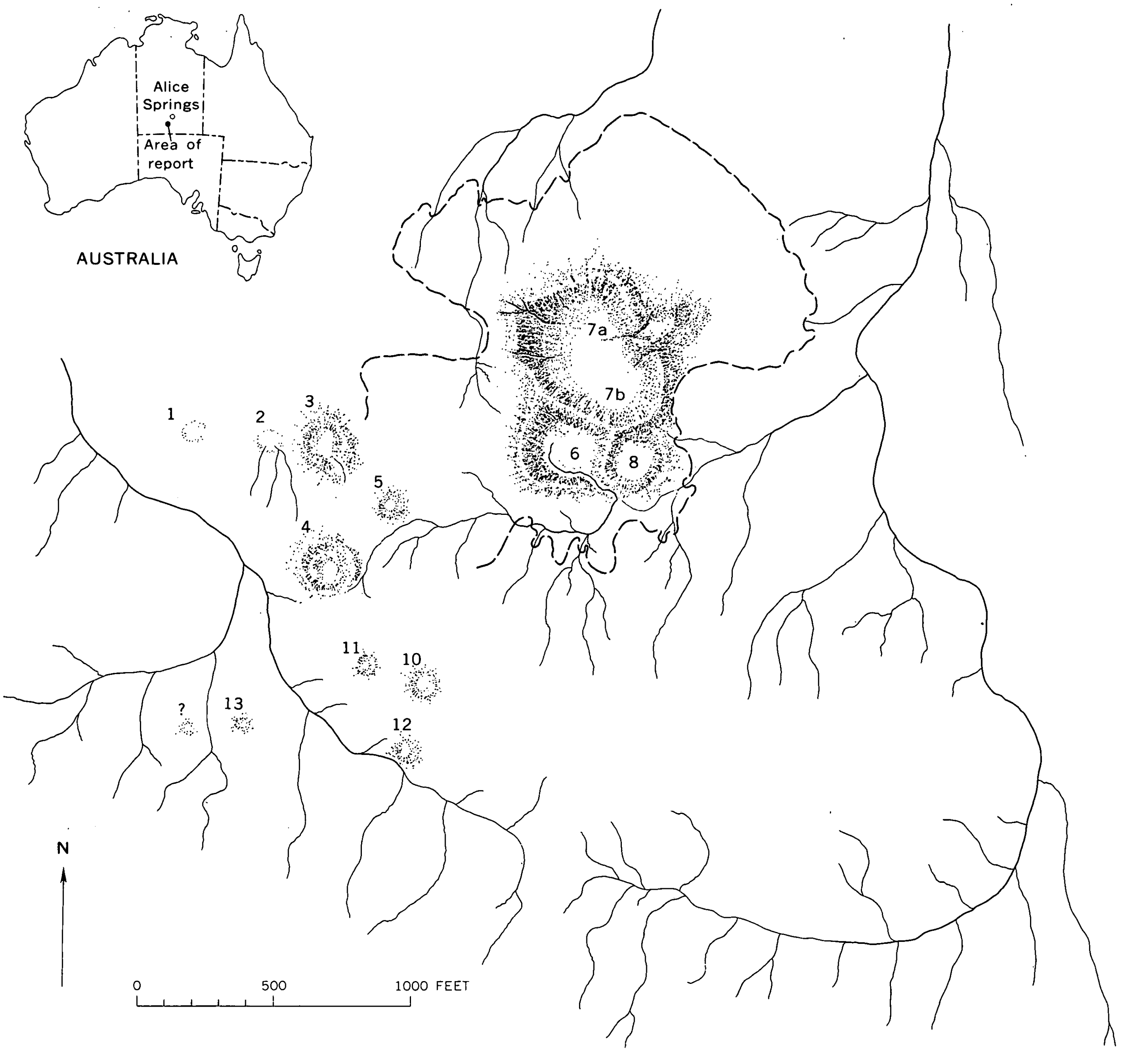

FIGURE 1.—Outline map of the Henbury crater field. Dashed line indicates approximate outer limit of ejecta from the larger craters. Based on aerial photographs in the Division of National Mapping, Australia, and on planetable survey by D. J. Milton and F. C. Michel.

Crater 4.—Crater 4 has a diameter of 190–220 feet, a depth of 12–20 feet, and a maximum rim height of 5 feet. As at crater 3, ejected blocks from sandstone beds in the predominantly shale bedrock sequence lie along rays. One ray, composed of blocks from a 6-inch-thick sandstone bed, starts at the foot of the raised rim about 50 feet beyond the crest on the west side of the crater and extends radially outward 230 feet. The outer 100 feet of the ray is marked only by a few blocks, which lie in a wet-weather water course. The fact that they have not been transported suggests that the craters formed relatively recently.

Crater 5.—Crater 5, nearly destroyed by erosion, is a circular crater 55 feet in diameter and not over 3 feet deep. A 1-foot-high rim is preserved on the south and west sides.

Crater 6 (Water Crater).—Crater 6 is 280–320 feet in diameter and about 20 feet deep; the rim is generally

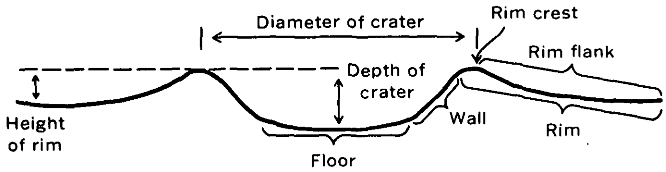

FIGURE 2.—Diagram illustrating terminology and measurements of craters used in this report.

5–10 feet high but is higher along the common wall with crater 7. The wall of this crater has been breached, and a rill system, which before the impact drained to the northeast, has been captured and now drains into the crater.

Crater 7 (Main Crater).—Crater 7 is an oval 600 feet long and 35–50 feet deep and has a maximum rim height of 20 feet (fig. 6). Crater 7 actually consists of two coalescing craters, which are designated craters 7a and 7b. The diameter of crater 7a is about 480 feet, and that of crater 7b, about 390 feet.

Crater 8.—Crater 8 is 230 feet in diameter. The depth generally ranges from 5 to 12 feet, increasing to over 20 feet at the common wall with crater 7. The maximum rim height, aside from the common walls with craters 6 and 7, is about 5 feet.

Crater 9.—It is uncertain what feature corresponds to the "illdefined and doubtful" crater noted by Alderman (1932) southeast of crater 8. It may be a depression along the beheaded drainage system, but it is probably not a crater.

Crater 10.—Crater 10 is 80–100 feet in diameter and 3–7 feet deep and has a maximum rim height of 4 feet. This crater is described in detail in a later section of this report.

Crater 11.—Crater 11 has a diameter of about 45 feet. The original form has been destroyed by excavation in search of meteoritic iron (apparently unrewarded), but it was very shallow and low rimmed.

Crater 12.—Crater 12 is 80–95 feet in diameter. As it lies on the south slope of a sandstone ridge, the depth measured at the north wall reaches 18 feet, and at the south a wall only a few inches high separates the crater floor from a watercourse about 1 foot lower. The west and southeast sides show a distinct raised rim reaching a height of 3 feet. Bedrock in the walls has been deformed so that the strikes are tangential, and beds near the rim crest are overturned.

Crater 13.—Crater 13 is about 20 feet in diameter and 3 feet deep. The rim height is at most a few inches. About 450 pounds of meteoritic iron was recovered at a depth of 7 feet in this crater (Spencer, 1933a).

Other possible craters.—A probable rimless crater about 25 feet in diameter lies about 200 feet west-southwest of crater 13 in pediment gravel (fig. 1). A possible crater was noted at the circular patch of alluvium just south of crater 8 (pl. 1), and another just southeast of crater 4, where the structures exposed in the gully appear to indicate a center of impact outside crater 4. Hodge (1965) reported an additional crater (his crater 15) about 25 feet in diameter about 40 feet northeast of the crest of crater 12. This was not noticed during my fieldwork, and it may be only an erosional hollow at the base of a sandstone hogback.

STRUCTURE OF THE CRATERS

Current knowledge of the structure of meteorite craters is based largely on detailed investigations of Meteor (Barringer) Crater, Ariz. (Shoemaker, 1963), and the Odessa, Tex., craters (Evans, 1961), which have been considered type examples of two structural varieties of meteorite craters (Shoemaker and Eggleton, 1961). These craters were formed in horizontal strata and, hence, have an essentially radial symmetry. Because of the dip of the strata at Henbury, the mechanics of deformation varied from point to point around the crater walls. Moreover, the interaction of stresses originating at the points of impact of separate fragments of the meteorite in the centers of craters 6, 7a, 7b, and 8 add to the complexity of the structure. Fortunately, the Henbury craters are considerably younger than Meteor Crater and the Odessa craters and have been less affected by erosion of the walls and rim than Meteor Crater or by infilling than Odessa. Rather dissection of the larger craters has reached a nearly ideal point—the spurs between gullies have retreated only slightly from the original crater walls, and cross sections of the walls can be examined in the gullies. Much of the walls is covered by colluvium, but exposures are well distributed so that structures updip, downdip, and along the strike from the centers of impact can be examined.

STRUCTURE OF CRATER 10

Crater 10 (fig. 3) exhibits many of the structural features of the larger craters even though it is smaller and was formed in more competent rocks. It is described here as an introduction to the more complex craters of the main group. The crater lies on the crest of the bare sandstone ridge. The crater walls and rim are a chaos of sandstone fragments, but the blocks of the more massive sandstone beds show consistent attitudes and indicate the patterns of deformation.

The north, or updip, wall of the crater has a very gentle slope of about 15° and exposes apparently undisturbed beds that dip southward 30°—the approximate preimpact attitude. The lack of deformation suggests that, with the direction of radial stress lying so

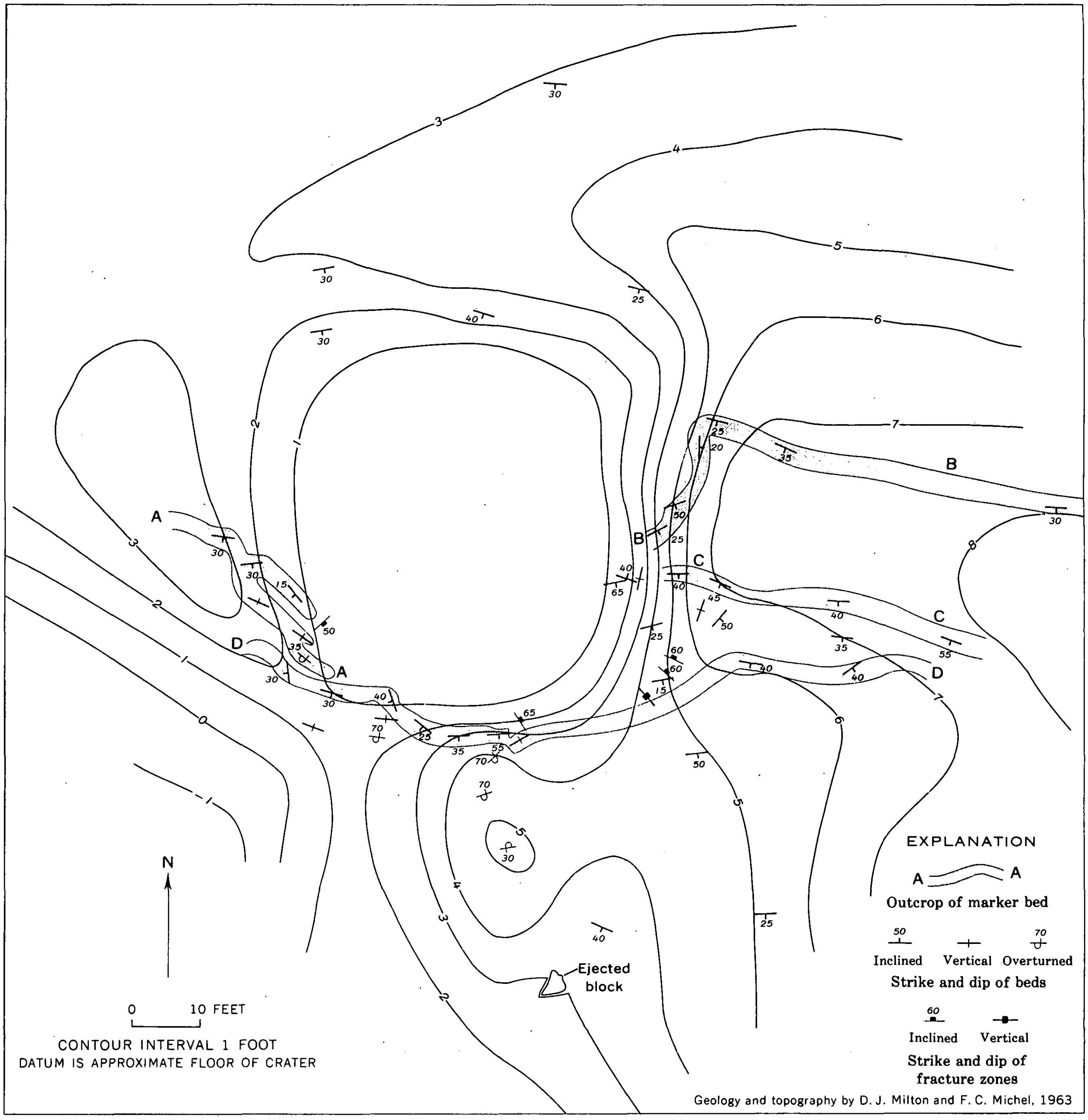

FIGURE 3.—Geologic map of crater 10.

near to the plane of bedding, little effective shear was exerted beneath the original crater wall, which is the boundary surface above which material was thrown out of the crater.

On the west side of the crater, a thick sandstone bed (fig. 3, bed A) curves from its normal east-west strike outside the crater to a nearly tangential northwest strike in the crater wall. Within the wall, the dip of the bed steepens upward from 15° near the base to pass through the vertical and become overturned at the rim crest. On the east wall, one sandstone bed (bed B) has been deformed into a broad open anticline with its axis radial to the crater. Elsewhere in the east wall, zones of rock that retain their preimpact attitudes with near-radial strikes alternate with zones in which strikes are tangential. The zones are separated by steeply dipping radial fractures. Some fracture zones are several inches wide and contain sandstone fragments parallel to the fracture.

In the south wall, the original tangential strikes were little changed, but beds generally steepen from their preimpact attitude at the base to become vertical and, finally, overturned at the rim crest. One thin-bedded sandstone unit shows a Z-shaped fold in which the upper and lower limbs retain approximately their original attitude and the middle limb is overturned (fig. 4). A block measuring 4 by 3½ by 1½ feet, which lies 37 feet beyond the crest of the south rim and probably was derived from a bed that struck through the central part of the crater, is the largest single ejected block at any of the craters.

FIGURE 4.—South wall of crater 10. The thin sandstone beds are overturned in the central limb of a tight Z-shaped fold 1 foot to the right of the hammer head.

Crater 10 is markedly rectangular, having its walls parallel to the east-west strike and the north-south regional joint system. This orientation contrasts with that of Meteor Crater, Ariz. (Shoemaker, 1963), which also has a square outline but has its diagonals along the rectangular regional joint grid. The bending to the south rather than to the north of bed B on the east rim suggests that the focus of energy release was somewhat north of the center of the crater.

STRUCTURES RELATED TO A SINGLE LARGE CRATER

Probably nearly all the rock exposed in the crater walls of the large craters has been displaced outward [1] from its preimpact position. Such displacement has in general reoriented bedding so that the strike tends to be tangential to the crater, or parallel to the crater walls. The smooth flexure of units e through h at the southeast end of the Main Crater presents an unusually simple example of this displacement. Eleswhere a variety of mechanisms determined by particular combinations of the stress environment and the preimpact rock geometry were involved in the outward displacement and produced structural features of characteristic types.

The structure of the large craters (figs. 5 and 6) is described in the following pages and is illustrated by a series of cross sections through the crater walls and rims (pl. 1).

The structures in the walls are described in terms of folds and faults, but these are not quite the structures produced during ordinary tectonic deformation. Folds are not continuous like those formed by slow intragranular movement but are mosaics formed by the reorientation of fracture-bounded blocks that are themselves little deformed. The fractures are usually so closely spaced—commonly on the order of an inch or inches—that, except under close inspection, they appear as continuous smooth folds. Similarly, surfaces at which originally separate bodies of rock are juxtaposed are called faults, although, as discussed in a later section, mechanisms different from the ordinary slippage of blocks in contact with one another were involved.

CRATER WALLS

FOLDS WITH STEEPLY DIPPING AXIAL PLANES

Although folding and faulting are closely associated in the crater walls, folding dominates in the north wall of crater 7a, where bedding before impact dipped inward at an angle slightly greater than the slope of the present crater wall. The dominant structure produced by the impact is an anticline that has a nearly horizontal axis extending along much of the lower slope of the north wall of the crater. Part of its trace is marked by the outcrop of unit a, which, as a projection downdip from the outcrop beneath the pediment gravel in the gully at the northwest of the crater indicates, would normally lie at an elevation below that of the crater floor. The anticline is asymmetric—the craterward limb retains nearly the original dip of the beds, and the short outer limb has been rotated through more than 120° and is now vertical or locally overturned. Along much of the anticline (as in section *B–B′*) the inner limb is thrust over the crest.

In addition, the north wall shows tight small-amplitude folds that have axial planes roughly parallel to that of the main anticline, and open folds that have axes radial to the crater. The outlying patch of unit b west of the line of section *B–B′* is preserved in an open radially plunging syncline. Such cross folds are char-

[1] The reference point for inward and outward is the center of the crater, such that beds may be said to dip outward into the crater wall.

FIGURE 5.—Aerial view of craters 6, 7, and 8 from the south. Reproduced from Hodge (1965) through the courtesy of the author.

FIGURE 6.—View of Main Crater from the northwest rim. Ejected bedrock in foreground with pediment gravel behind. Photograph by Douglass Baglin.

acteristic of the inner limb of the main anticline, though tangential folds predominate on the outer limb and higher on the crater wall.

The expression of the main anticline as a ridge persists because units a and b have slightly greater resistance to erosion than unit c. The ridge is probably not, however, a product entirely of differential erosion but an original feature of the immediate postimpact topography. If so, the original crater wall would not have been a single conical or concave surface, as the simplest mechanical theory of cratering would suggest. Some craters produced by hypervelocity impact of projectiles into pyrex retain a doughnut-shaped ring of material at the intersection of the steep, upper wall and the flatter floor (H. J. Moore, oral commun., 1964). Although folding is not involved in these, the similarity of crater profile may indicate a somewhat analogous pattern of stresses. Many large craters on the moon show irregular concentric structures on the inner walls. These have usually been interpreted as the result of slumping into the crater, but some may be folds that were produced at the time of impact.

FOLDS WITH LOW-DIPPING AXIAL PLANES

The major structure exposed in the lower part of the south, or downdip, wall of crater 7a (section *E–E'*) is, as in the updip, north wall, an anticline whose axial plane is approximately vertical. Higher in the wall the outward dip steepens to become vertical, and the beds in the upper half of the slope are overturned. Superimposed on this broad structure are a series of small folds that have axial planes dipping at low angles into the crater and at least one minor thrust fault parallel to the axial planes of these folds (figs. 7, 8). These folds are very shallow—they are seen on the upper bank of the gully but almost die out near its floor. These folds and minor thrusts apparently formed as the result of shearing stresses that varied irregularly in intensity on different planes parallel to the original crater wall (the surface along which shear was sufficient to displace rock over the crater rim). These shear folds are thus fundamentally different from the compressional folds that occur, for example, in the lower part of this wall or in the opposite north wall. Folds of this type

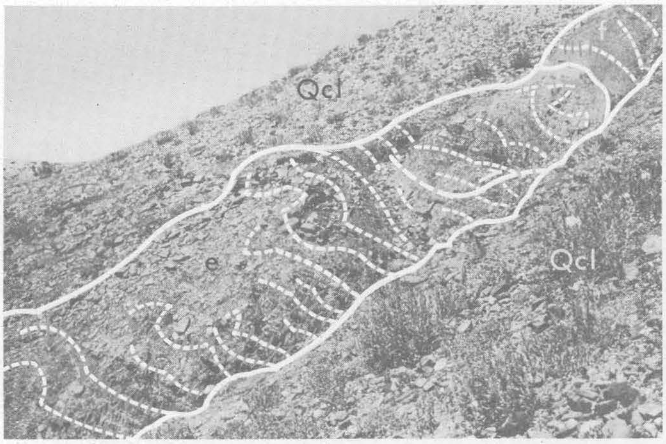

FIGURE 7.—View of the east bank of gully on the south wall of the Main Crater near the line of section *E–E′*, showing increase in dip in the upper wall and shallow folds whose axial planes are approximately parallel to the crater wall. Map units e and f are bedrock units; Qcl is postcrater colluvium. Photograph by M. R. Dence.

would be destroyed rapidly by erosion and perhaps were more abundant in the freshly formed crater.

A somewhat different type of fold having a nearly horizontal axial plane is best illustrated by section *D–D′*. Bedding in this part of the wall of the Main Crater appears little deformed except within a small area in the middle slope. Here the rock is displaced outward in a fold concave toward the crater. In the upper part of this broad fold is a smaller but much sharper fold with the same sense. The base of the main fold is in part a thrust surface on which the folded rocks moved outward over the unfolded rocks. The axial plane of the upper fold dips inward at about 10°, and the basal surface of the main fold has a low dip also. The entire structure appears to have been produced by a punchlike stress whose principal axis lay at an angle lower than that of the present crater wall.

THRUST FAULTS

Thrust faults have been mentioned above in association with each type of fold in the crater walls. In parts of the crater walls, thrust faulting is more prominent than folding. In the west wall of the Main Crater, the shock waves at impact were propagated nearly along the original planes of bedding. Reorientation of bedding into the present tangential attitudes, with the strike at nearly right angles to the preimpact strike, was apparently accomplished largely by folding, but thrust faulting also occurred. The broad structural features along the line of section *A–A′* are an anticline whose axis is in the midslope and a syncline in the lower wall that brings unit b to the surface. The more obvious, although perhaps more superficial, features are an imbricate series of thrust plates in the lower wall. The lowest discontinuity is a sharply defined surface dipping 30° inward, along which vertical beds are thrust outward over gently dipping beds. The thrust fault may be considered as occupying the axial plane of the syncline. The gentle inward dip of the underlying plate increases outward, particularly at a sharp synclinal bend, to a second discontinuity which consists of a disturbed zone about a foot wide (shown as a thrust fault on the map) in which both faults and folds occur. The next underlying plate repeats the pattern of gentle inward dips steepening outward and is terminated at the outer edge by a small tight anticline. Beyond this anticline the gentle inward dip prevails again to the axis of the major anticline. These shallow structures represent localized outward

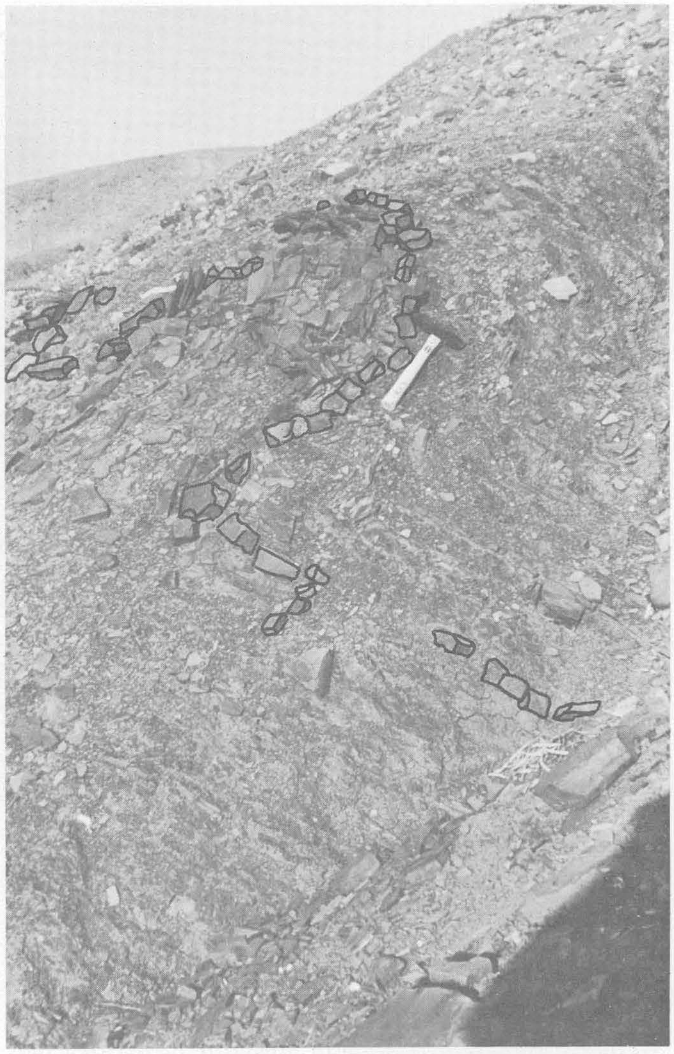

FIGURE 8.—Closeup of folds having low-dipping axial planes at center in figure 7. A single bed of hard sandstone has been emphasized.

displacements superimposed on the broader folds. Thrusting was dominant nearest the crater, both thrusting and folding occurred in the middle, and folding was dominant farthest out.

The wall at the west end of the Main Crater about 60 feet south of the line of section *A–A′* shows features resembling those of both sections *A–A′* and *B–B′*. As in section *B–B′*, an asymmetric anticline has the inner limb thrust over the crest. Above the gently dipping and locally horizontal inner limb is another thrust fault. The plate above this thrust consists of steeply dipping beds and may be a continuation of the inner plate to the north along the line of section *A–A′*.

COMBINED STRUCTURES IN THE WATER CRATER

The walls of the Water Crater show all the structures described above. On the south wall, sandstone beds are folded about gently dipping axial planes and are displaced along at least one shallow thrust fault and an apparent tear fault (section *H–H′*). The sandstone (subunit hs) on the rim flank consists mostly of broken ejecta from the beds exposed in the wall. To the east, the tops of the shales of unit h and the band of sandstone (bed hs_3) on the crater rim are indeterminate, and these beds may form an inverted rim flap.

On the west wall (section *G–G′*), steep- and shallow-dipping folds are not distinctly separable as in the Main Crater, and the characteristics of both types are shown in a single anticline that has a curved axial surface. The trace of the axial surface of this fold is intersected twice by the line of section *G–G′*; in the upper outcrop band of bed hs_1 it dips at a steep angle, and some 6 feet up the wall it is again intersected as an overturned fold that has a low dip. The entire folded bedrock sequence has been thrust outward. The pediment gravel exposed low in the wall may be continuous with that on the rim, but it more likely is preserved in a syncline below the thrust, as indicated in the cross section. Beds in the isolated patch of units h and hs on the rim crest do not match the lithology of any of the beds in nearby parts of the wall, and the preimpact position from which they were thrust (or perhaps thrown out, as there is no evidence that they are not upside down) is unknown.

CRATER RIMS

The distinction between debris and disturbed bedrock in crater rims at Henbury is much less clearcut than at Meteor Crater (Shoemaker, 1933), and the two have not been explicitly distinguished on the map. Attitudes were, however, recorded wherever consistent orientations could be found, so that areas of bedrock units on the rims without attitude symbols on the map may be assumed to consist of small fragments with little or no common orientation (this is not necessarily true of areas on the walls, where colluvium hinders the measurement of attitudes). In these patches, however, the fragments are entirely or predominantly from a single bedrock unit. The mixed ejecta map unit consists for the most part of thoroughly mixed fragments of several bedrock units and pediment gravel. In some areas, particularly on the southeast rim crest of the Main Crater, this unit includes discrete patches or bands of monolithologic ejecta that can be distinguished but are too small and discontinuous to be mapped.

SYNCLINAL FOLDS AT THE RIM

The structural style of coherent ejecta on the rim is related to the style in the walls below. In section E–E′ the dips in the upper part of the wall of the Main Crater progressively steepen through vertical to an overturned attitude. This synclinal structure is continued on the rim, where the three bedrock units e, f, and g form a flap lying in inverted sequence upon pediment gravel. The exposed band of pediment gravel between bedrock in the upper crater wall and the rim flap is in places as narrow as 1 foot (fig. 9). The consistent attitudes of bedding within the flap indicate much greater structural coherence than would be found in throwout piled in inverted sequence by ejection along ballistic trajectories. On the other hand, the greatly reduced thickness of each of the three units in the flap in comparison with the thicknesses exposed in the crater wall and the pinch-out of unit f near the outer edge of the flap show that the flap cannot simply be the overturned limb of a fold. The flap must actually consist of thin slices that were formed by strong shearing, which took place simultaneously

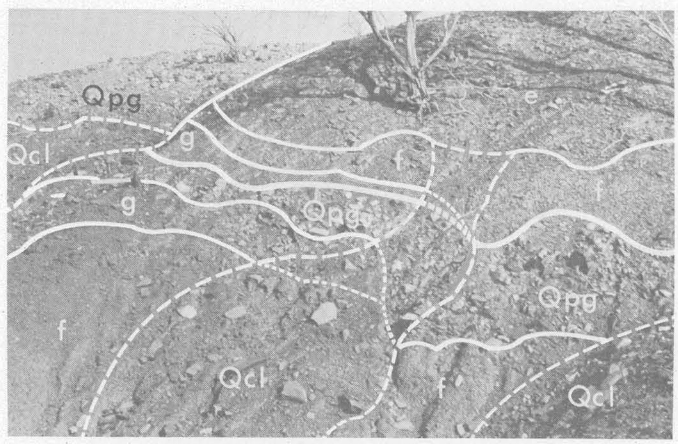

FIGURE 9.—Overturned rim flap overlying pediment gravel, south rim of Main Crater slightly west of line of section E–E′. From bottom to top are bedrock units in place, pediment gravel, and bedrock units in the overturned flap. Map units e, f, and g are bedrock; Qpg is pediment gravel; Qcl is postcrater colluvium. Weighted line is a fault.

with the outward rotation of the whole pile, along planes lying at small angles to the bedding. The minor structures in this part of the flap, such as the two plunging inverted synclines, probably reflect the topography on which the flap fell.

The extension of the flap far down the wall of the Water Crater suggests that the Water Crater is fractionally older than the Main Crater. If the shock wave propagated outward from the centers of impact at a speed of 640 meters per second—the average shock speed measured in alluvium at the Sedan nuclear cratering event (Nordyke and Williamson, 1965)—displacement of rock near the rim of craters 6 and 8 began at about 80 milliseconds and 120 milliseconds after impact. If the shock propagation was slower—in accordance with the slower arrival times recorded at the Scooter high explosive cratering event (Hess and Nordyke, 1961)—corresponding values are 120 and 190 milliseconds. The time intervals between the impacts in the larger craters are probably negligible in comparison. Farther southwest, ejecta from the Main and Water Craters appear to have interpenetrated and intermingled, but the pattern is not at all clear.

Northeast of the line of section E–E′, the rim flap shows a somewhat different structure. Bedding in the material immediately above pediment gravel at the crater lip is right side up, as indicated by primary sedimentary features, but within a few feet outward it is folded through nearly 180° to form a thin overturned flap (fig. 10). The axis of the fold, which has at least one radial offset, can be traced for about 60 feet along the rim. The same type of synclinal rim folding as that shown in section E–E′ apparently occurred, but in addition, a major outward thrust developed along a surface that intersected the lower limb of the syncline, so that the axial region is preserved, thrust over the pediment gravel.

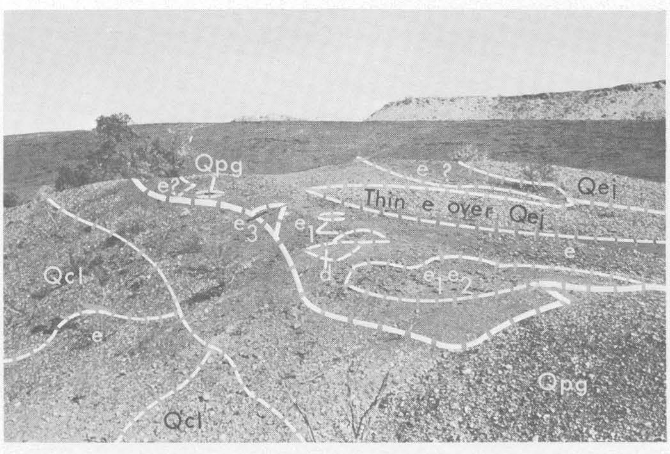

FIGURE 10.—Southwest rim of Main Crater showing thin ejecta layer, composed mostly of overturned beds of unit e, overlying pediment gravel. Tops of trees growing in the Water Crater at left, sandstone ridge in middle background, and main ridge of Bacon Range at right background. Units d, e, e_1, e_2, and e_3 are bedrock; Qpg, pediment gravel; Qej, mixed ejecta; Qcl, postcrater colluvium. Weighted line is a fault.

THROWOUT AND FALLOUT

Throwout debris crops out in a broad belt surrounding the large craters except where it has been removed by erosion, as south and east of crater 8, or buried beneath later alluvium, as east of the Main Crater. The absence of exposed throwout debris on the steeper parts of the rim flank, as northwest of the Main Crater, is probably the result of erosion or burial, although much of the mapped pediment gravel could be throwout debris from pediment gravel that lay within the limits of the crater.

At its inner limit throwout debris from bedrock units cannot be clearly differentiated from coherent ejecta. Within the area on the northwest rim of the Main Crater shown on plate 1, fragments of units b, c, and d lie in zones in inverted sequence on pediment gravel and were probably ejected along ballistic trajectories. An approximate outer limit of throwout from the larger craters is shown in figure 1. In the outer parts of the zone, west and north of the Main Crater, throwout debris is generally a few inches thick, but in some broad mounds it is nearly 2 feet thick. Some mixing of debris from different units occurs, but exposures are commonly monolithologic. Fragments from unit d apparently dominate in the outer part of the throwout west and northwest of the Main Crater.

No exposures of material corresponding to the fallout debris of Meteor Crater (Shoemaker, 1963) were found. Probably, however, fragments of impact glass are remnants of a fallout layer from crater 7a that has been destroyed by erosion. Such glass is most abundant in approximately the area of throwout on the north rim of crater 7a and decreases in abundance outward. Scattered fragments were also found more than 2,000 feet east of the craters. According to Spencer (1933b), tear-shaped drops and threads were found along a narrow strip of ground extending eastward a mile from the crater. This pattern probably indicates an original asymmetric distribution of fallout, although possibly the smaller fragments were transported by wind.

STRUCTURES RELATED TO TWO CRATERS

Figure 11 shows the approximate outlines of the craters that would have been produced around each center of impact had there been no mutual interference. The distances between craters 7a and 6 and between craters 7b and 8 are great enough that little interaction

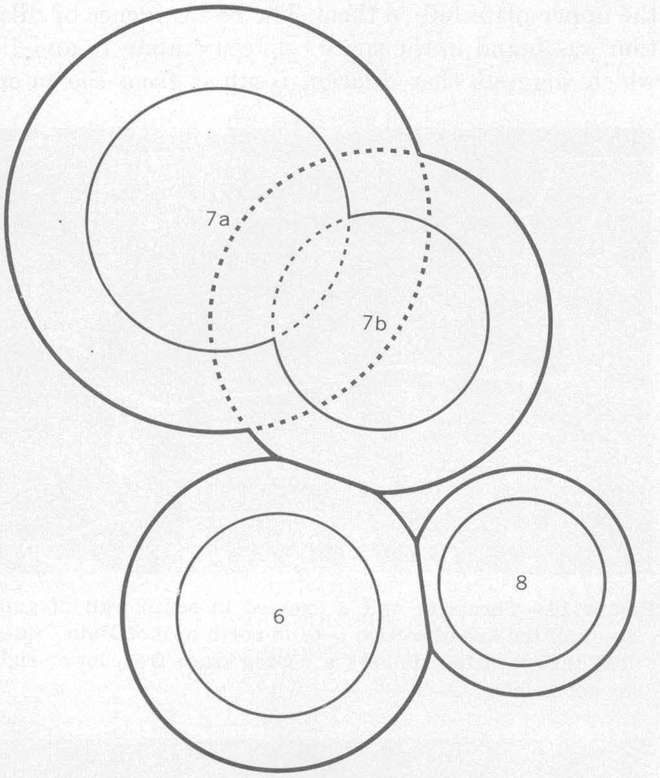

FIGURE 11.—Diagram showing relationship of the larger craters. Heavy lines indicate rim crests, light lines base of walls; dotted lines complete craters 7a and 7b as either would be had the other not formed.

would be expected, and no evidence of it was found, although exposures of bedrock in the critical areas are not good.

The two pairs of craters 7b and 6 and 6 and 8 are closer. The common walls in both pairs have a folded internal structure. The outcrop and attitude pattern of sandstone beds of subunit hs in the wall between craters 6 and 8 indicates a broad syncline with a pair of tight folds in the axial region. The wall between craters 7b and 6 shows a series of folds (section *F–F′*). A syncline near the crest is best shown by a sandstone bed somewhat east of the line of section. The principal fold must be anticlinal because the bedrock at the crest lies at least 20 feet higher than its preimpact elevation. The plunging anticline slightly south of the crest may be the main fold (the intricate folding on its south limb is probably shallow shear folding related only to crater 6). The structure at depth is unknown; a series of décollements along small thrusts seems likely.

The centers of impact in 7a and 7b were so close that the intervening wall did not survive, at least above the level of the present alluvial crater floor, except as short spurs at either end projecting from the common wall of the Main Crater. The spur on the south shows bedrock that strikes northeast-southwest overall and dips southeast but is folded into a series of folds whose axial planes trend at right angles to the general strike (fig. 12). The inner two folds have curved axial surfaces and are tight folds with an overturned limb between them; the outer two are much more open. The pattern suggests that the bedding was bowed into a strike tangential with crater 7a and compressed radially from crater 7b, probably accompanied by a buttressing effect from the northward movement of the wall of crater 6.

On the northern wall of the Main Crater, the prominent spur at the intersection of craters 7a and 7b has diverted drainage to form deep gullies on either side. The complexities of structure in this area (the most complex found at Henbury) in part result from displacement of separate masses of rock outward from the two centers of impact and in part result from significant displacement only by stresses from one center but facilitated by dilation of the rock caused by interaction of the two stress fields.

The structure on the face of the spur at the intersection of craters 7a and 7b mirrors that of the corresponding spur on the opposite side of the Main Crater. The general trend of strike is at right angles to the line joining the centers of craters 7a and 7b (although no attitudes could be measured in subunits e_1 and e_3, the ground surface apparently is close to a dip slope near the southern nose. Cross folds, such as are shown at the southeast end of section *D–D′*, were produced by outward compression. The entire moderately dipping sequence is thrust outward. Bedding in the outer edge of the thrust plate has been folded up into a synclinal bend. Below this plate is another thrust slice that is also internally folded. The line of section *D–D′* intersects the outcrop of this slice in the outer limb of an anticline

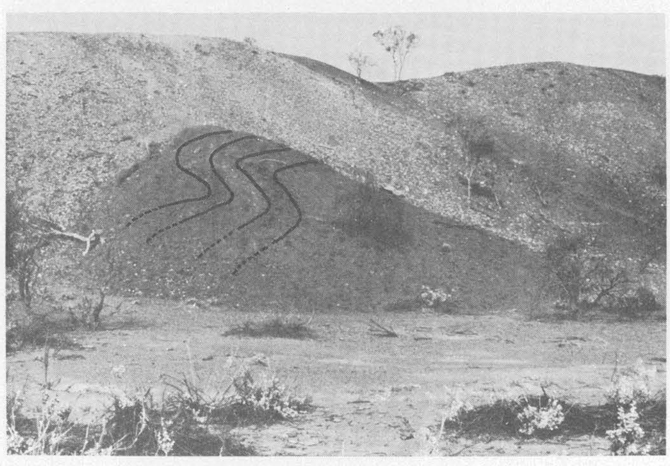

FIGURE 12.—Spur at the intersection of craters 7a and 7b on the south wall of Main Crater. Folds are indicated by the outcrop pattern of two outlined sandstone beds in unit e.

whose inner limb is best exposed southeast of the gully in the outcrop area of subunit e_2.

On the opposite side of the spur, a series of thrust slices can also be seen. Along the line of section *C–C′* the outcrops nearest the crater belong to a plate of rock that retains approximately its preimpact attitude. The rock below and outside this plate has been rotated more than 90° through an arc concave upward, so that bedding is overturned and dips north (fig. 13). The lower zone, which is itself part of a thrust slice, has been displaced outward relative to the upper plate, so that the break between them is at least locally a surface of underthrusting. Exposures farther out in the gully continue to show steep northward dips and probably represent the outward continuation of the lower zone. Indicators of bedding tops are lacking in these beds, however, and the possibility of isoclinal folding cannot be eliminated.

The surface of the discontinuity between the upper and lower zones as exposed on the south side of the gully is not smooth but irregularly stepped, so that motion of the upper and lower plates would have been impossible while they were in contact. Figure 14 shows a small block along this surface in which bedding is oriented nearly at right angles to the bedding below and above. The block could have acquired its orientation only while out of contact with the adjacent blocks. Such features indicate that deformation in the wall occurred during an instant of dilation, which allowed structural blocks in the wall to deform and rotate independently of each other, after which the whole mass settled into its present position. Perhaps it is going too far to suggest that the divergent beds at the top of the lower zone in figure 15 were pushed out in opposite directions when the upper plate fell on them. The best evidence of dilation was found in the space between craters 7a and 7b, which suggests that dilation resulted from the inter-

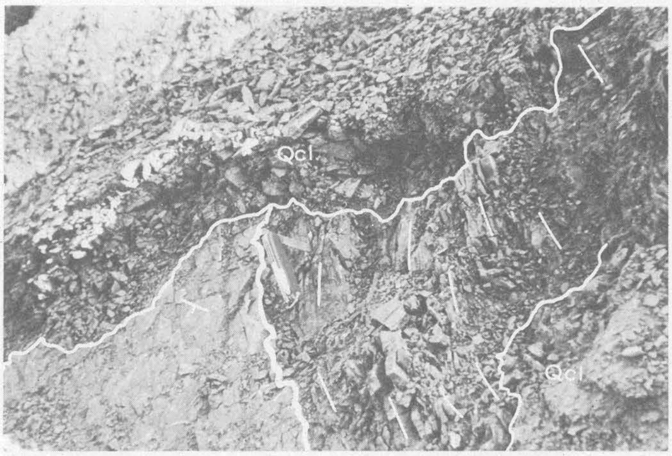

FIGURE 13.—Underthrust in unit d near base of north wall of Main Crater along the line of section *C–C′*. Flat faces at left are the top surfaces of beds in the upper plate dipping toward the crater at front and left. In the lower plate at right beds are overturned and tops face toward the left. Map unit Qcl is post-crater colluvium.

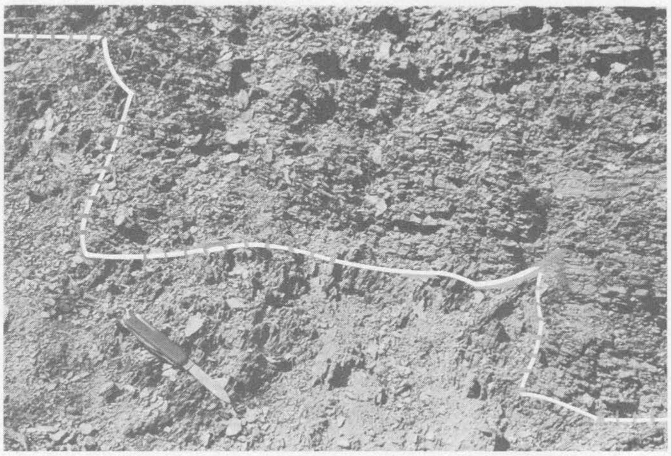

FIGURE 14.—Thrust in unit d exposed in south wall of gully south of the line of section *C–C′* in north wall of Main Crater. The thrust surface follows a zig-zag trace from lower right to upper left.

FIGURE 15.—Detail along same thrust surface as shown in figure 14. The block in center must have been rotated to its vertically dipping attitude during a moment of greater separation of the adjacent blocks. Qcl is post-crater colluvium; bx breccia.

action of stress from craters 7a and 7b. Nowhere in any of the Henbury craters, however, were slickensides or gouge related to the impact found, and even fine-grained breccia (except as ejecta) is rare. This suggests that dilation, or at least light contact of structural blocks, during deformation of the crater walls was the rule even where only one center of impact was involved.

Between the lines of sections *C–C′* and *D–D′*, the series of thrust slices may be followed continuously from the crater wall onto the rim. The highest slices in the pile tend to have low craterward dips, corresponding to the inner plates along the two lines of section. At the head of the gully northwest of the spur, bedding is seen to turn down and under in an overturned anticline with an overthrust of small slip along the axial surface (figs. 16 and 17). Beneath the inverted limb is a complex thrust zone of broken bedrock, and below that is pediment gravel. Apparently the main overthrust mass rolled over its own outer edge like a caterpillar tread, producing a feature resembling on a small scale an Alpine nappe. The inverted limb of the fold is in a somewhat analogous structural position to the outer limb of the fold in the middle slice in section *D–D′*, except that the inverted limb has been thrust farther out and lies beyond the outcrop of the pediment gravel.

A prominent ridge extends northeast from the intersection of craters 7a and 7b to well beyond the area mapped on plate 1. This ridge may be compared to ridges at right angles to the line joining the centers of intersecting craters formed by the simultaneous detonation of separate equal-sized buried explosive charges (Vortman, 1965). At Henbury the axis of the ridge appears to bend so that, although the inner portion is at right angles to the line of centers, the outer portion is more nearly radial to the larger crater.

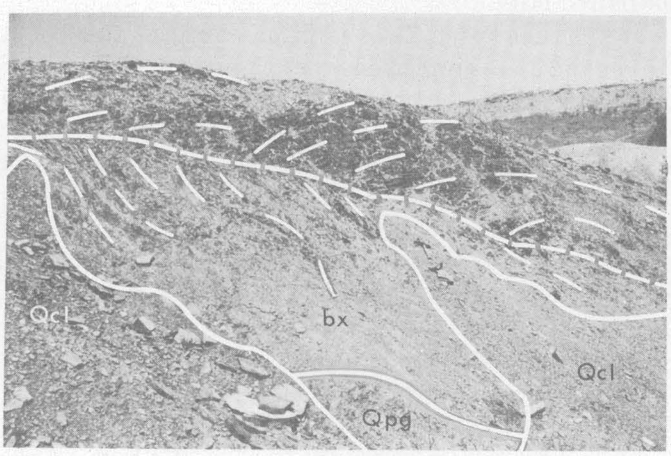

FIGURE 16.—Nappelike folded thrust slice in south bank of gully in north wall of Main Crater south of line of section *C–C′*. The fold axis (dashed line) is in part a thrust surface. Above are gently dipping beds of unit e; below are overturned beds grading downward into breccia (bx); and at bottom is pediment gravel (Qpg) over which the entire nappe has ridden. Qcl is postcrater colluvium. Photograph by M. R. Dence.

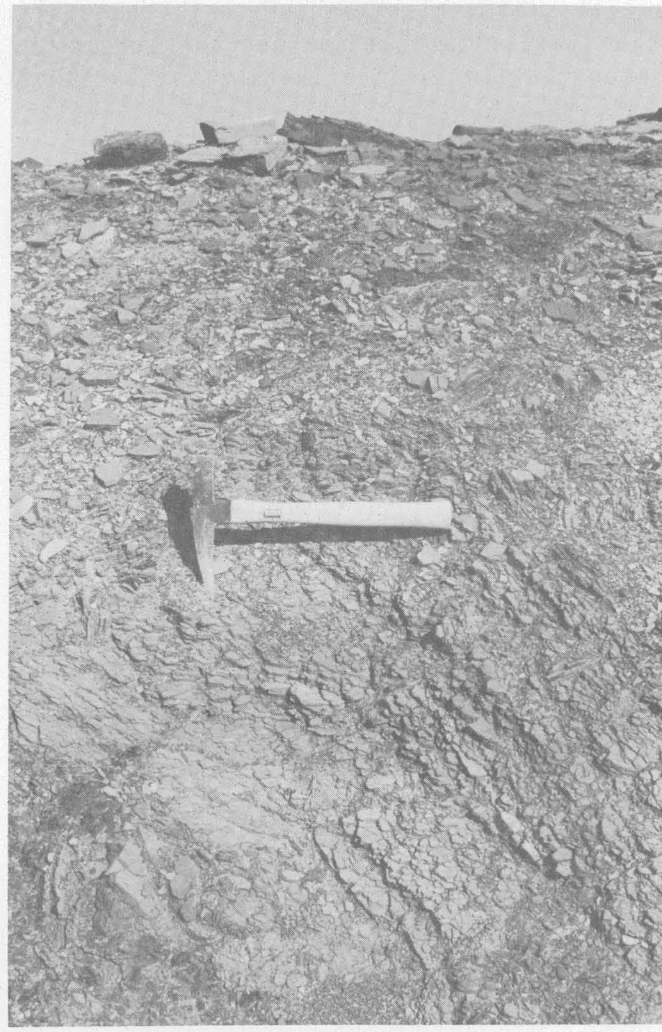

FIGURE 17.—Axial region of nappelike folded thrust slice in north wall. Area shown is at extreme upper left in figure 16. Beds above hammer are right side up; beds below are overturned; and beds at lower left are brecciated.

The diminishing frequency of attitude symbols on plate 1 outward along the ridge reflects a steadily increasing degree of brecciation but indicates that structurally coherent thrust slices can be followed for 80 feet over the precrater ground surface. Farther out, ejecta from different bedrock units becomes increasingly mixed, and the contact between the ejecta from specific units and the mixed ejecta is drawn somewhat arbitrarily. The stratigraphic relation of the mixed and unmixed ejecta is uncertain—it could be a lateral transition or an overlap with either unit on top. The sides of the ridge are cut by shallow gullies at right angles to its length (just visible in fig. 5). Slight differences repeated from gully to gully in the composition of the ejecta on the inner and outer walls suggest that erosion was controlled by an original corrugated pattern of throwout.

CHARACTER OF DEFORMATION

The variety of structural features in the walls of the craters at Henbury in large part reflects the range of orientation of the deforming stress. Stress in nearly horizontal planes, which tends to occur low in the craters, usually produced tangential compressional folds that have approximately vertical axial planes. Underthrusting accompanied such folding principally where dilation from simultaneous impacts loosened the wallrock. Sharply localized outward stress within the walls produced relatively uncommon folds that are concave toward the crater and have flat-lying axial planes.

Overthrusts were produced by stress at higher angles of elevation. Thrust faulting was most extensive where stresses from two centers of impact were active simultaneously but also occurred in simple craters.

Folds having axial planes parallel to the crater wall indicate stress at a still higher angle of elevation. Such folds are particularly susceptible to erosion and were perhaps more common in the fresh crater than in the existing exposures.

Stress at an even higher angle produced overturned rim flaps. The occurrence of such rim flaps on the south rim of crater 10 as well as at crater 7a and perhaps the Water Crater suggests that they developed particularly where the bedding dips away from the crater. Finally, debris in inverted stratigraphic sequence was ejected along ballistic trajectories by stress acting at the highest angles of elevation.

COMPARISON WITH OTHER IMPACT CRATERS

Shoemaker and Eggleton (1961) have suggested that impact craters are of two structural types. In the Barringer (Meteor Crater) type, upward folding of planes that were horizontal before impact increases from the unaffected terrain outside the crater inward to the crater wall and from below up to the ground surface and culminates in an overturned synclinal flap at the rim. The Odessa type is characterized by an anticline whose axial surface crops out in the upper crater wall; the upturning in the rim is not carried so far as to form a rim flap. Outward-dipping underthrust faults occur in the walls of the Barringer type, and inward-dipping overthrusts in the walls of the Odessa type. Largely by analogy with craters produced by buried nuclear devices, the differences were attributed to a larger scaled depth of penetration of the meteorite in the Barringer than in the Odessa type. The 24-kilometer diameter Ries crater in south Germany was suggested as a variant of the Odessa type, characterized by imbricate slices on the rim (the "Schollen" and "Schuppen" of Bentz, 1927), which were attributed to the greater relative importance of gravity in the mechanics of so large a crater.

The characteristics of all three structural types can be found in the Henbury craters. In the Main Crater, anticlinal folds dominate in the lower wall and synclinal folds nearer the rim, as in some experimental hypervelocity impact craters.[2] A shallower depth of burst would tend to produce anticlinal folding nearer the rim, as in the Odessa craters. The absence of anticlinal folding in the lower walls at Barringer Crater may be due to the greater competence of the rock rather than the stress pattern. The factors controlling overthrusting (aside from dilation by simultaneous impacts) are not clear, but certainly large size of the crater is not essential. The structural features at each crater certainly provide information on the mechanics of crater formation; yet their variety, even within a single crater field such as Henbury, suggests that many more impact craters must be mapped before a comprehensive synthesis of impact mechanics can be made safely.

BOXHOLE CRATER

One day was spent at the Boxhole Crater at Dneiper (formerly Boxhole) Station, 185 miles northeast of the Henbury craters. The similarity of chemical composition and general appearance (particularly the prevalence of shrapnellike twisted fragments) of meteoritic iron at Henbury and Boxhole suggests that the two may be paired falls.

In the time spent, little additional information could be obtained to supplement the original description of Madigan (1937). A crude planetable sketch confirmed Madigan's statement that the crater is nearly circular and has a diameter of about 575 feet. The crater lies on the south side of a ridge of schist and gneiss containing many silicified zones and quartz veins (shown simply as quartz reef on the small scale geologic map of Smith, 1963). There is little mappable structure in the bedrock, so that only the crudest determination of the pattern of deformation seems possible.

Most of the ejecta from the crater appears white and contrasts with the red-brown color of undisturbed near-surface materials, apparently because the bulk of the exposed ejecta comes from below a weathered zone in which quartz has developed a heavy red stain. Weathered bedrock crops out at many places along the crater wall. The contact between the ejecta and bedrock is ex-

[2] This is best shown by craters in ductile material, such as wax (Frasier and Karpov, 1962).

posed around a bench on the southeast side of the crater and slopes gently outward.

Madigan believed that the less steep slopes at the Boxhole Crater indicate an age greater than that of the Henbury craters. But it is the south wall of the Main Crater that gives the impression of steepness at Henbury, and its steepness is probably an original feature caused by interaction with craters 6 and 8. If only the simple parts of the walls of craters 7a and 7b are considered, the average slope is, if anything, slightly less than at Boxhole Crater.

Qualitative comparison of the degree of erosional modification and of the very weakly developed weathering profiles on the ejecta at both the Boxhole and the Henbury craters suggests that the craters could be the same age.

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